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RECREATIONAL CRAFT PERFORMANCE STUDY - TRANSOM IMMERSION, PITCH AND HEAVE RESPONSE OF THREE PLANING CRAFT AT ZERO SPEED IN FLOLLOWING SEAS

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RECREATIONAL CRAFT PERFORMANCE STUDY TRANSON IMMERSION, PITCH AND HEAVE RESPONSE OF THREE PLANING CRAFT AT ZERO SPEED IN FOLLOWING SEAS

FINAL REPORT

SEPTEMBER 1975

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Transom immersion, pitch and heave responses for models of three planing craft at zero speed in following seas were determined. The test craft were free in heave and pitch but restrained in surge, sway, roll and yaw. Tests were made in both regular and irregular waves. The results for one model (Deep-Vee hull) displayed a marked nonlinear response in the heave and pitch responses for wave lengths approximately equal to the overall length of the craft. For two test conditions the John Boat model filled with water as a result of an inflow over the transom.

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The work reported herein was accomplished for the U. S. Coast Guard's Office of Research and Development, Marine Safety Technology Division, as part of its program in Recreational Boating Safety.

The contents of this report reflect the views of Stevens Institute of Technology, Hoboken, New Jersey, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policy of the Coast Guard. This report does not constitute a standard, specification, or regulation.

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CASTLE POINT STATION
HOBOKEN, NEW JERSEY

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September 1975

RECREATIONAL CRAFT PERFORMANCE STUDY

Transom Immersion, Pitch and Heave Response of Three Planing Craft at Zero Speed in Following Seas

by

Richard I. Hires

for

The United States Coast Guard
DOT-CG-43152-A

(DL Project 390/4209)

Approved

Daniel Savitsky
Deputy Director

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ABSTRACT

Transom immersion, pitch and heave responses for models of three planing craft at zero speed in following seas were determined. The test craft were free in heave and pitch but restrained in surge, sway, roll and yaw. Tests were made in both regular and irregular waves. The results for one model (Deep-Vee hull) displayed a marked nonlinear response in the heave and pitch responses for wavelengths approximately equal to the overall length of the craft. For two test conditions the John Boat model filled with water as a result of an inflow over the transom.

KEYWORDS

Planing Craft

Seakeeping

TABLE OF CONTENTS

NOMENCLATURE

a	regular wave amplitude
g	acceleration of gravity
$H_{1/3}$	irregular wave significant height
I_{yy}	pitch moment of inertia about center of gravity
L	boat length
LCG	distance from top of transom to center of gravity
R_y	pitch radius of gyration
s	$\frac{2\pi a}{\lambda}$
VCG	distance from keel to center of gravity
$Z_{1/3}$	significant "height" of the heave response in irregular waves
z	heave
λ	wave length for regular waves
$\Theta_{1/3}$	significant "height" of the pitch response in irregular waves
θ	pitch
ζ	transom immersion
ω	regular wave angular frequency

INTRODUCTION

The objectives of this model study were to determine the heave and pitch response of three planing craft at zero speed in following seas and also to determine transom immersion. The three craft used in this study were representative of three popular hull configurations for recreational craft, namely, the deep vee hull, the cathedral hull and the flat-bottom hull, typified by the John boat. For all tests the three models were restrained in yaw, roll, sway and surge and were free in heave and pitch. The response of the craft was measured for both regular and irregular following seas. For regular waves, the wavelengths were varied over a range from one-half to twice the overall length of each craft tested. The amplitude of the regular waves was varied from the maximum obtainable* to about 25% of this maximum value. For the irregular waves, the average "period" of the waves was approximately equal to the period of a regular wave train with wavelength equal to the overall length of the test boats. The significant height was approximately 4% of the overall length of the boats.

In addition to recording heave, pitch, and transom immersion for each test, 16mm, color motion pictures of selected tests were taken. The movies of each filmed test have been spliced together into one 600 foot reel which will be forwarded to the Coast Guard with this report. Table V of this report is a log of the test conditions for each filmed test and is intended as an aid to viewing the film.

For the tests in irregular waves, the time history of the incident wave elevation at a point 8 feet aft of the test model, heave, pitch and transom immersion were recorded on both a visicorder and on magnetic tape. The statistics for the irregular wave tests included in this report were obtained from reading the visicorder records. The magnetic tape recording of these irregular wave tests is on file at the Davidson Laboratory and is available to the Coast Guard upon request.

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*For the longer wavelengths the maximum obtainable amplitude was determined by the capacity of the mechanical wavemaker. For the shorter waves the criterion for maximum amplitude was to generate the highest stable (non-breaking) wave.

EXPERIMENTAL APPARATUS AND PROCEDURE

Table 1 is a list of the prototype and model characteristics of the three craft used in this study. The three types of planing hulls were adapted from the midship sections (John Boat and Deep-Vee) or body plan (Cathedral Hull) of recreational craft tested by the Wyle Laboratories.[1] The prototype total weight, engine weight, hull weight and load as tested at Wyle Laboratories are also reported in Reference 1. By making estimates of the location of the center of gravity of each component of the total weight, the center of gravity and pitch moment of inertia of each prototype craft could be calculated. The corresponding values of these parameters for each model were obtained by suitable arrangements of ballast weights.

The tests were performed in the Davidson Laboratory Tank No. 2, which is a square tank 75 feet on a side and 4-1/2 feet deep. Along one side of the tank there is a plunger-type wave maker capable of producing both regular and irregular waves. The period and stroke of the plunger are continuously adjustable which allows, within limits, for regular waves of specified heights and lengths to be produced. For irregular waves the stroke of the plunger is held constant while the frequency is changed between each cycle. The irregular wave consists of about 100 waves with statistical properties controlled by the wave maker input program, the stroke setting on the wave maker and the time required to complete the 100-step input program.

On the side of the tank facing the wave maker there is a beach to absorb the incident waves. The beach provides sufficient absorption to keep reflected wave energy to within reasonable limits.

The models were placed in the tank at a distance of 34 feet from the wave maker. A heave mast, free to move only in the vertical, was attached to each model through a free-to-pitch pivot box installed in the model. The axis of the pivot was at the center of gravity of the model.

The heave and pitch responses of the models were sensed by linear differential transformers. The signal from each transducer was amplified, filtered and recorded. A careful calibration of the heave and pitch transducers revealed a linear dependence of signal output on heave and pitch displacement, respectively. The amplitude of the heave and pitch response in regular waves was obtained by measuring the amplitude of the signals on the visicorder record and by using the known calibration rates.

The incident waves were measured using a stationary resistance-type wave probe located 8 feet aft of the models. A similar wave probe was used to estimate transom immersion. This second probe was attached to the model at the top of the transom. The probe was aligned such that its axis was perpendicular to the keel of the model. The transoms of the three test craft were not perpendicular to the keel but were at oblique angles of 105° for the John Boat and Deep-Vee models and 100° for the Cathedral Hull. Therefore, at the keel, the separation between the transom and the wave probe used to measure transom immersion was approximately $1\frac{1}{2}$ inches for the John Boat, 2-3/4 inches for the Deep-Vee Craft and $1\frac{1}{2}$ inches for the Cathedral Hull.

Static calibrations of both the stationary and transom-attached wave probes revealed a linear dependence on depth of immersion of the probes over a range of 10 inches of immersion. The signals from each wave probe were amplified, filtered and recorded.

For the tests in regular waves, the incident wave, heave and pitch records were nearly sinusoidal with nearly constant amplitude. The amplitude of each signal could be readily determined. The phase of the pitch and heave response relative to the incident wave could also be satisfactorily measured. The incident wave was measured 8 feet aft of the LCG of the test model. The phase of the incident wave at the LCG of the model could be calculated from linear wave theory. The difference in phase between the pitch or heave response and the incident wave (at the location of the LCG) was then determined by calculating the time difference between an identifiable phase of the pitch (or heave response) i.e., peak or trough, and the corresponding phase of the incident wave. For several

test conditions, the record of the transom-attached wave probe, while periodic, departed markedly from a sinusoidal variation. This was believed to be due to the wave wire being subjected simultaneously to the incident wave and the wave system generated by the oscillatory boat model. Consequently, only the amplitude of this signal was determined.

For the tests in irregular waves the significant incident wave height, and significant heave and pitch "heights" were determined. The height of the incident waves was measured from the visicorder oscillographs. Height was defined as the difference in water elevation from a peak to the following trough with a descending zero crossing between. The significant height is the average of the highest one third wave heights. The significant "height" of the pitch and heave records in irregular waves were determined in an exactly similar manner. The record of the transom-attached wave probe in irregular waves was not analyzed. Since the local wave disturbances at the transom generated by the model were also sensed by the probe, the number of waves recorded during the irregular wave program was significantly greater than the number of incident waves (approximately 100). Consequently, the statistics of this signal were not solely dependent on the incident wave.

TEST RESULTS

Tables II, III, and IV are summaries of the test results for both regular and irregular following seas for the Cathedral Hull, John Boat and Deep-Vee models, respectively. All results are presented as non-dimensional ratios in order to facilitate application to prototype craft.

The heave response, z/a , in regular waves plotted against the non-dimensionalized wave frequency, $\omega^2 L/g$, is shown in Figures 1, 2, and 3 for the Cathedral Hull, John Boat and Deep-Vee models, respectively. The pitch response, θ/s , as a function of dimensionless wave frequency for each craft is presented in Figures 4, 5 and 6. For all models and at each regular wave frequency studied, tests were made at three wave heights corresponding to the nominal maximum wave height obtainable at each particular frequency and to approximately 60% and 25% of this highest wave.

For the Cathedral Hull and Deep-Vee models, repeat tests in the largest waves were made at most of the wave frequencies. The wave heights in the repeated tests were in each case slightly greater than those obtained in the initial maximum wave tests but never more than 110% of the initial values. As an aid to interpreting the results presented in Figures 1-6, the points representing corresponding wave height conditions at the various wave frequencies have been connected by straight lines segments.

From Tables II, III, and IV and Figures 1 through 6, it is evident that both the heave and pitch response decrease with increasing wave frequency (or decreasing wavelengths) while the transom immersion to wave amplitude ratio increases with increasing wave frequency. The heave responses of the Cathedral Hull and John Boat models were nearly identical over the range of wave frequencies investigated. The heave response of the Deep-Vee model at the smallest wave height is similar to that of the John Boat and Cathedral Hull. At the middle and highest wave height, the Deep-Vee model heave response was similar to the others for short wave lengths as well as the longest wave length, but for a wave length equal to the model length the Deep-Vee heave response is significantly greater than that of the other models. The pitch response for the John Boat was significantly less than that for the Cathedral Hull at wavelengths nearly equal to the length of the models. For the Cathedral Hull and John Boat models the values of z/a and θ/s for the different wave heights used at each frequency display some scatter which could be attributed to both experimental error and to some nonlinearity in the heave and pitch response. For the Deep-Vee model the very large scatter, greater than 40%, in the heave and pitch response at $\omega^2 L/g = 6.29$ (i.e., $\lambda = 1.002L$) would strongly suggest a marked nonlinearity in the response of this craft.

In the irregular wave tests the heave response, $Z_{1/3}/H_{1/3}$ was nearly identical for all three models. The pitch response $\Theta_{1/3}$ was noticeably less for the John Boat than for the other two models. This result could be attributed to two factors: (1) The John Boat was approximately 20% longer than the other two models but all three were tested in irregular following seas possessing identical period and height statistics. Therefore the average wavelength to boat length ratio would be less for the

John Boat model than for the other two models. (2) The pitch response for the John Boat was less in regular waves than the pitch response for the other models for wavelengths approximately equal to the boat lengths and a lesser response in irregular waves could be expected.

For two tests in regular waves, the John Boat filled with water coming into the boat over the top of the transom. This occurred for the case of the maximum amplitude waves with wavelengths equal to the boat's length and $1\frac{1}{2}$ times the boat length. The ratio of the incident wave height to the transom height above the keel was 0.92 for the first case and 1.28 for the second.

Movies were taken of each model for two or more of the regular wave tests and for the tests in irregular waves. The camera speed was adjusted for the scale ratio such that when projecting the film at 16 frames per second, the time scale of the motions will correspond to the prototype time scale. Table V is a log of the test conditions for each filmed test to aid in the viewing of the movie.

CONCLUSIONS

The heave response in regular following seas showed no amplification and decreased monotonically with increasing wave frequency for the three recreational craft tested. A simple calculation to roughly estimate the expected natural frequencies of these craft in heave yields natural frequencies approximately twice the highest wave frequencies at which tests were conducted. The observed decrease in heave response for decreasing incident wavelength is a result of the decrease in the heave forcing function with decreasing wavelength.

The pitch response in regular waves displayed only a slight amplification, i.e., $\theta/s > 1.0$, at the lowest wave frequency for all three models. The expected natural frequency in pitch for these craft is again considerably higher than the highest wave frequency at which tests were conducted. It would appear that the slight amplification could be ascribed to experimental scatter.

The sinking of the John Boat for two regular wave tests poses serious questions in regard to the safe operation of this type of craft in following seas. This result may warrant further investigation of the John Boat both at zero speed and at slow forward speed in following seas with wave heights exceeding or comparable to the transom height. It should be noted that for the other two craft tested, the maximum wave heights were in all cases significantly less than the transom height.

Finally, the apparent nonlinearity in both the heave and pitch response of the Deep-Vee model may have an impact on the formulation of mathematical models which would reliably predict the time history or the statistics of the motion response of this type of craft in waves.

REFERENCE

1. White, R.W., Bowman, J.O. and Patrick, S.L., "Standards Analysis Powering/Performance Evaluation Using Test Course Methods." Preliminary Research Report, Vol.1, Wyle Laboratories, Huntsville, Ala., March 1974.

TABLE I

MODEL CHARACTERISTICS

CATHEDRAL HULL
Body Plan From Wyle Boat #1210

	Prototype	Model
Scale Ratio	1	3.5
Length overall, ft	15.34	4.38
Beam (max), ft	5.75	1.64
Transom height above keel, ft	2.48	.71
Test weight, lb	1152	26.86
LCG, ft	5.46	1.56
VCG, ft	1.08	0.31
I_{yy}, ft^2	25,580	48.70
R_y/L	.307	.307

JOHN BOAT
Midship Section From Wyle Boat #208

	Prototype	Model
Scale Ratio	1	2.5
Length overall, ft	14	5.60
Beam (max), ft	3.75	1.50
Transom height above keel, ft	1.11	.44
Test weight, lb	434	27.80
LCG, ft	4.16	1.66
VCG, ft	1.2	0.48
I_{yy}, ft^2 lb	7500	76.80
R_y/L	.297	.297

DEEP-VEE
Midship Section From Wyle Boat #1191

	Prototype	Model
Scale Ratio	1	4
Length overall, ft	18.77	4.69
Beam (max), ft	7.7	1.925
Transom height above keel, ft	3.33	.83
Test weight, lb	1800	28.1
LCG, ft	6.2	1.55
VCG, ft	1.38	0.35
I_{yy}, ft^2 lb	51,000	49.80
R_y/L	.28	.28

TABLE II

CATHEDRAL HULL MODEL

TEST RESULTS IN REGULAR WAVES

$\frac{\omega^2 L}{g}$	$\frac{\lambda}{L}$	$\frac{10^2 a}{L}$	$\frac{2\pi a}{\lambda}$	z/a Gain	z/a Phase	θ/s Gain	θ/s Phase	ζ/a Gain
2.95	2.137	1.065	0.031	1.018	353°	1.224	307°	0.661
2.95	2.137	3.729	0.110	0.934	356°	1.129	288°	0.714
2.95	2.137	6.469	0.190	0.853	359°	1.038	296°	0.718
2.95	2.137	6.659	0.196	0.817	53°	1.002	346°	0.664
3.93	1.600	1.084	0.068	0.702	20°	0.923	311°	0.877
3.93	1.600	2.892	0.114	0.743	7°	0.830	304°	1.026
3.93	1.600	5.194	0.408	0.776	8°	1.002	295°	1.048
3.93	1.600	5.403	0.212	0.764	355°	0.952	298°	0.968
5.87	1.073	1.046	0.061	0.509	21°	0.734	336°	1.960
5.87	1.073	2.150	0.126	0.495	21°	0.735	347°	1.960
5.87	1.073	3.158	0.198	0.602	355°	0.798	325°	2.300
12.01	0.525	0.761	0.091	0.175	11°	0.096	336°	2.275
12.01	0.525	1.617	0.194	0.129	355°	0.083	8°	2.118
12.01	0.525	1.903	0.228	0.190	333°	0.086	341°	2.420
12.01	0.525	2.207	0.264	0.172	344°	0.091	8°	2.490

TEST RESULTS IN IRREGULAR WAVES

$$10^2 H_{1/3}/L = 4.93$$

$$Z_{1/3}/H_{1/3} = 0.56$$

$$\Theta_{1/3} = 7.25^\circ$$

TABLE III

JOHN BOAT MODEL

TEST RESULTS IN REGULAR WAVES

$\frac{\omega^2 L}{g}$	$\frac{\lambda}{L}$	$\frac{10^2 a}{L}$	$\frac{2\pi a}{\lambda}$	z/a Gain	z/a Phase	θ/s Gain	θ/s Phase	ζ/a Gain
3.15	1.993	0.938	0.059	0.793	39°	0.990	336°	0.603
3.15	1.993	2.723	0.086	0.945	17°	1.093	321°	0.721
3.15	1.993	4.717	0.143	0.905	17°	0.945	328°	0.725
4.20	1.498	1.042	0.075	0.672	17°	0.790	335°	0.800
4.20	1.498	2.976	0.214	0.675	11°	0.812	332°	0.910
*4.20	1.498	4.955	0.355	0.859	14°	0.884	335°	1.500
6.36	0.989	0.967	0.061	0.477	8°	0.426	349°	1.350
6.36	0.989	2.188	0.139	0.503	31°	0.471	10°	1.600
*6.36	0.989	3.571	0.227	0.517	22°	0.494	359°	1.660
12.56	0.501	0.491	0.062	0.242	322°	0.071	333°	1.700
12.56	0.501	0.923	0.116	0.266	322°	0.089	344°	1.900
12.56	0.501	1.667	0.209	0.295	350°	0.081	345°	2.310

TEST RESULTS IN IRREGULAR WAVES

$$10^2 H_{1/3}/L = 3.60$$

$$Z_{1/3}/H_{1/3} = 0.54$$

$$\Theta_{1/3} = 5.27^\circ$$

*Boat sank.

TABLE IV

DEEP-VEE MODEL

TEST RESULTS IN REGULAR WAVES

$\frac{\omega^2 L}{g}$	$\frac{\lambda}{L}$	$\frac{10^2 a}{L}$	$\frac{2\pi a}{\lambda}$	z/a Gain	z/a Phase	θ/s Gain	θ/s Phase	ζ/a Gain
3.16	1.996	1.048	0.032	0.847	7°	0.989	299°	0.627
3.16	1.996	3.536	0.111	0.698	9°	1.084	291°	0.714
3.16	1.996	5.455	0.172	0.932	351°	1.178	293°	0.863
3.16	1.996	5.792	0.182	0.690	346°	0.922	277°	0.844
4.21	1.495	1.102	0.046	0.726	20°	0.972	320°	1.130
4.21	1.495	2.665	0.112	0.787	11°	1.075	311°	1.430
4.21	1.495	4.815	0.202	0.815	355°	0.921	298°	1.260
4.21	1.495	4.886	0.205	0.843	357°	0.990	304°	1.180
6.29	1.002	0.977	0.061	0.527	310°	0.577	269°	1.180
6.29	1.002	1.954	0.122	0.727	3°	0.837	330°	2.540
6.29	1.002	2.772	0.174	0.865	10°	0.960	336°	2.370
6.29	1.002	3.092	0.194	0.816	351°	0.837	323°	2.730
12.86	0.490	0.711	0.091	0.250	344°	0.077	344°	2.180
12.86	0.490	1.510	0.191	0.200	2°	0.083	355°	2.440
12.86	0.490	2.097	0.269	0.228	353°	0.089	356°	2.695

TEST RESULTS IN IRREGULAR WAVES

$$10^2 H_{1/3}/L = 4.25$$

$$Z_{1/3}/H_{1/3} = 0.55$$

$$\Theta_{1/3} = 7.25^\circ$$

TABLE V

TEST CONDITIONS FOR FILMED TESTS

Run No.	Model	Wave Characteristics λ/L	10^2 a/L	Comments
41	Deep Vee	Irregular Waves		
42	Deep Vee	1.002	2.772	
43	Deep Vee	1.996	5.445	
45	John Boat	1.993	2.723	
48	John Boat	1.498	2.976	
54	John Boat	0.989	2.188	
55	John Boat	0.989	3.571	Boat sinks
56	John Boat	Irregular Waves		Run no. is shown after test
60	Cathedral Hull	2.137	6.469	
66	Cathedral Hull	1.073	3.158	
69	Cathedral Hull	0.525	0.761	
70	Cathedral Hull	1.600	5.403	
71	Cathedral Hull	2.137	6.659	
73	Cathedral Hull	Irregular Waves		

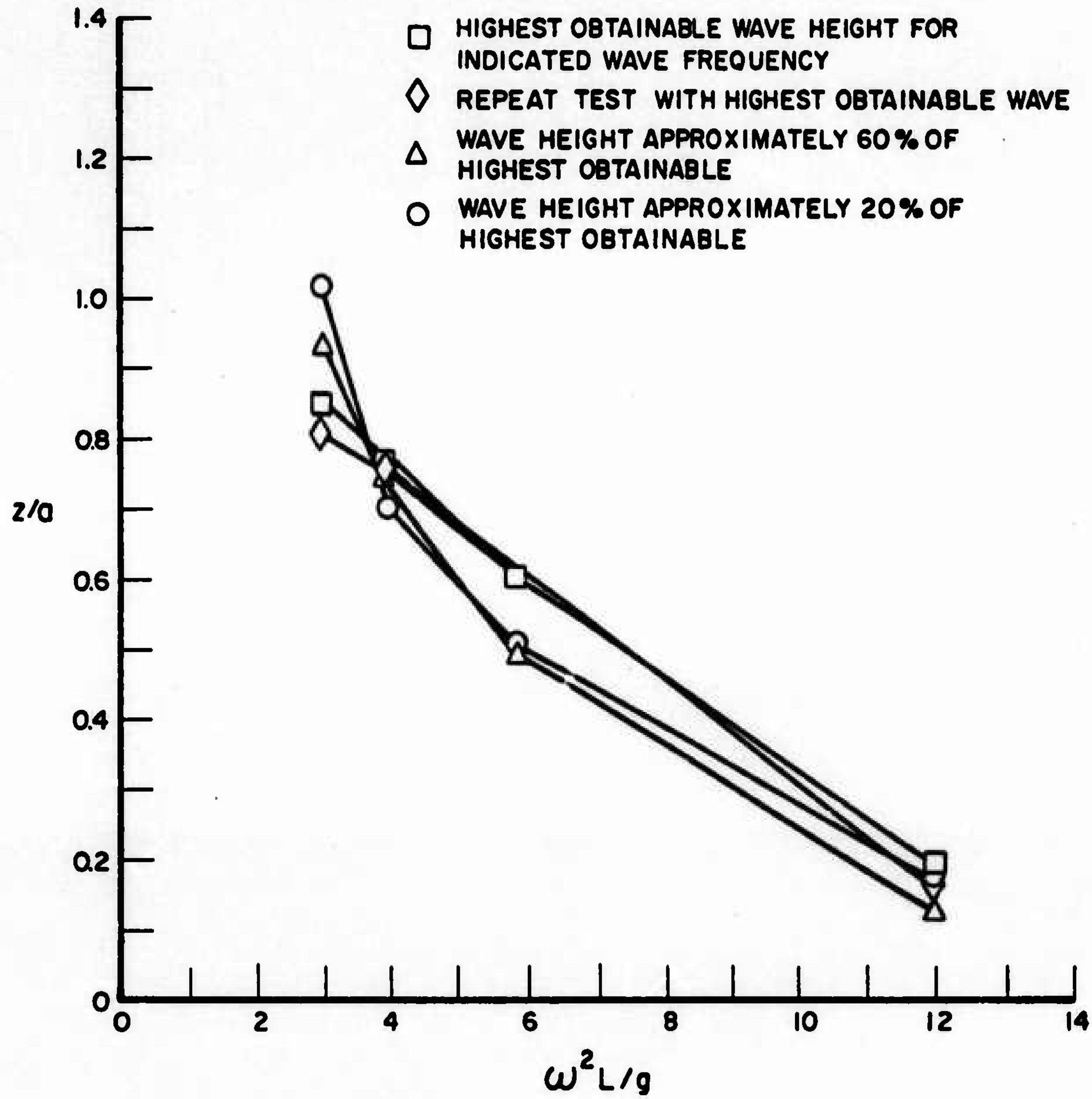

FIG. 1. HEAVE RESPONSE OF THE CATHEDRAL HULL MODEL

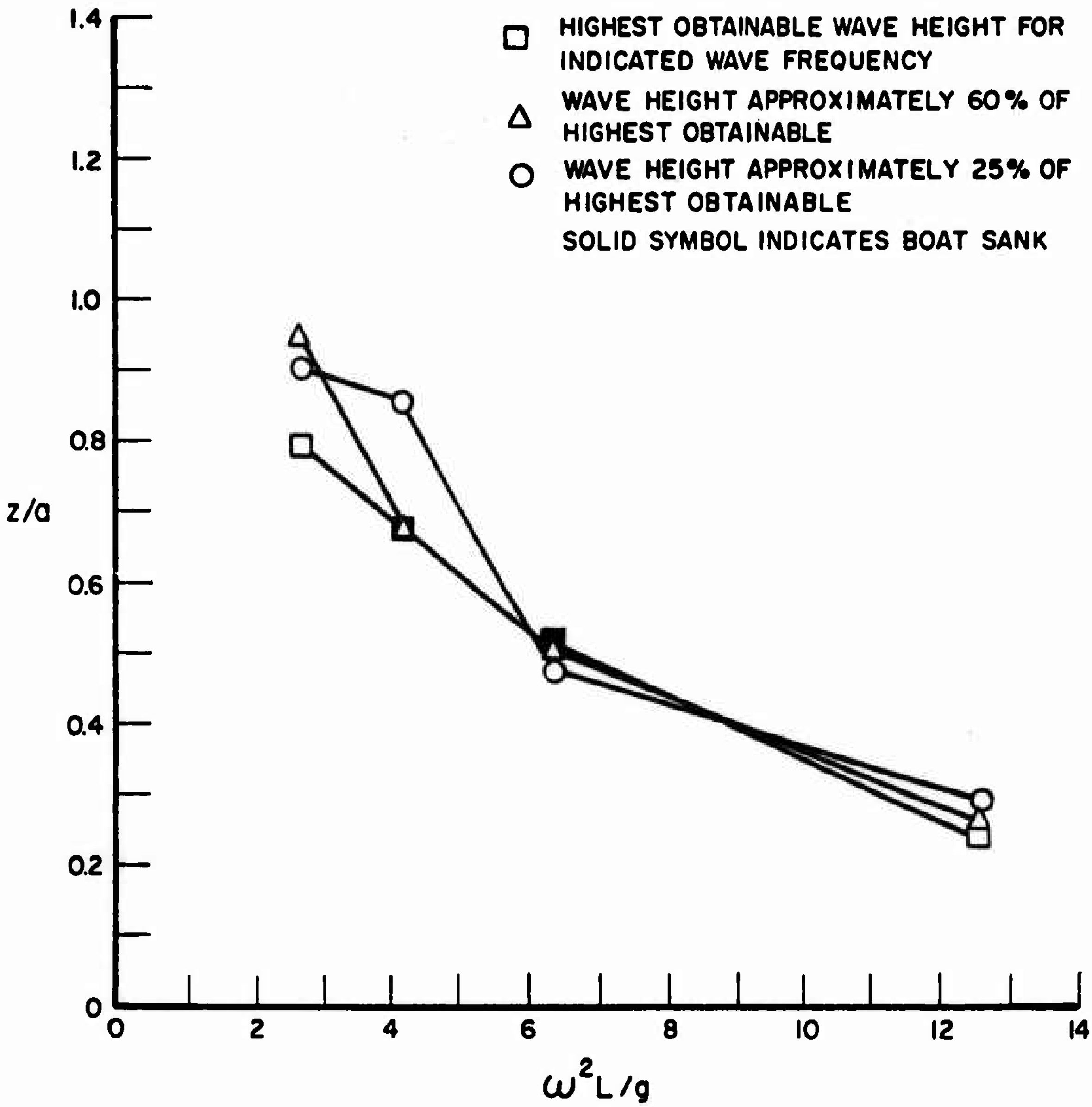

FIG. 2. HEAVE RESPONSE OF THE JOHN BOAT MODEL

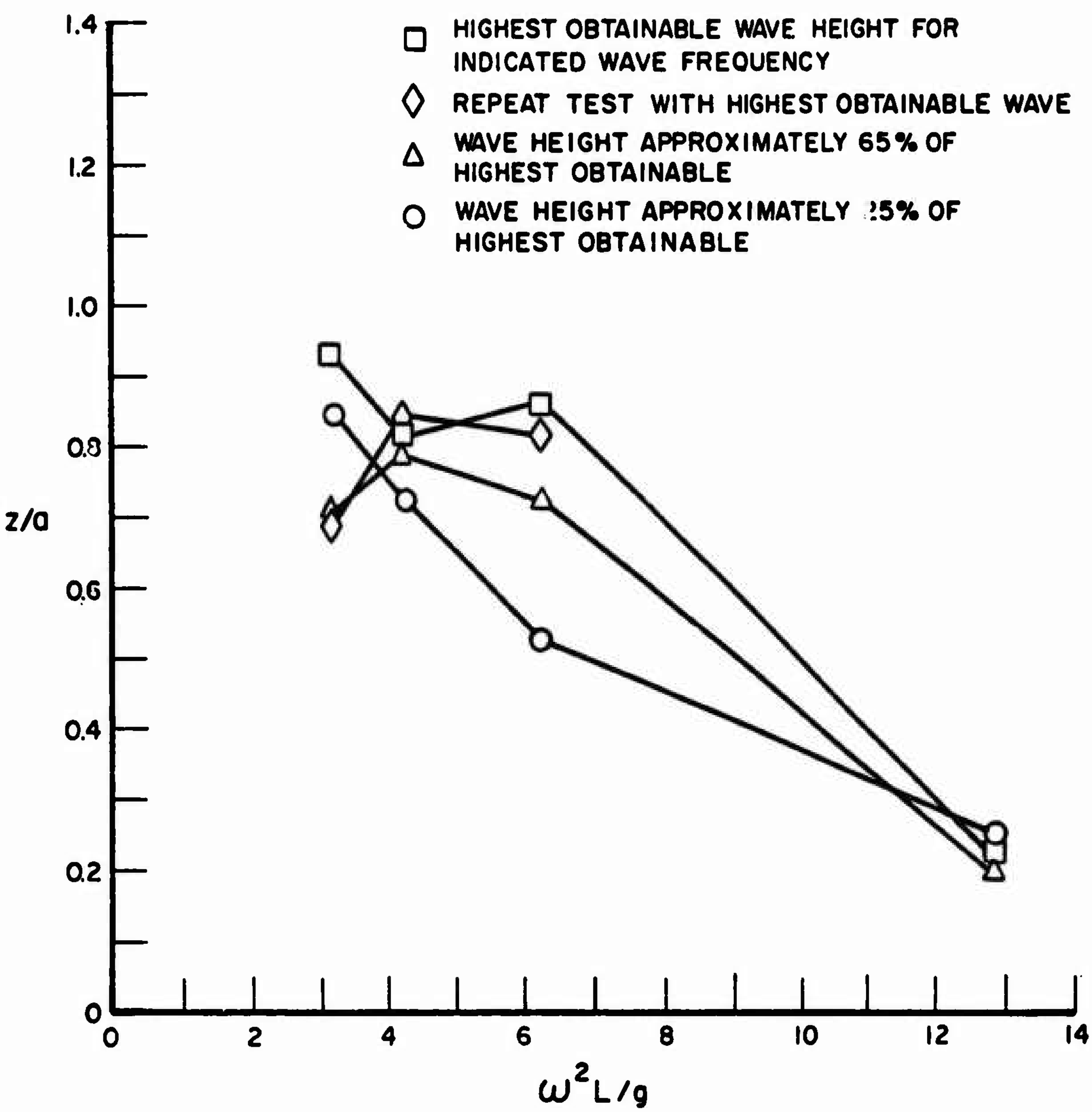

FIG. 3. HEAVE RESPONSE OF THE DEEP VEE MODEL

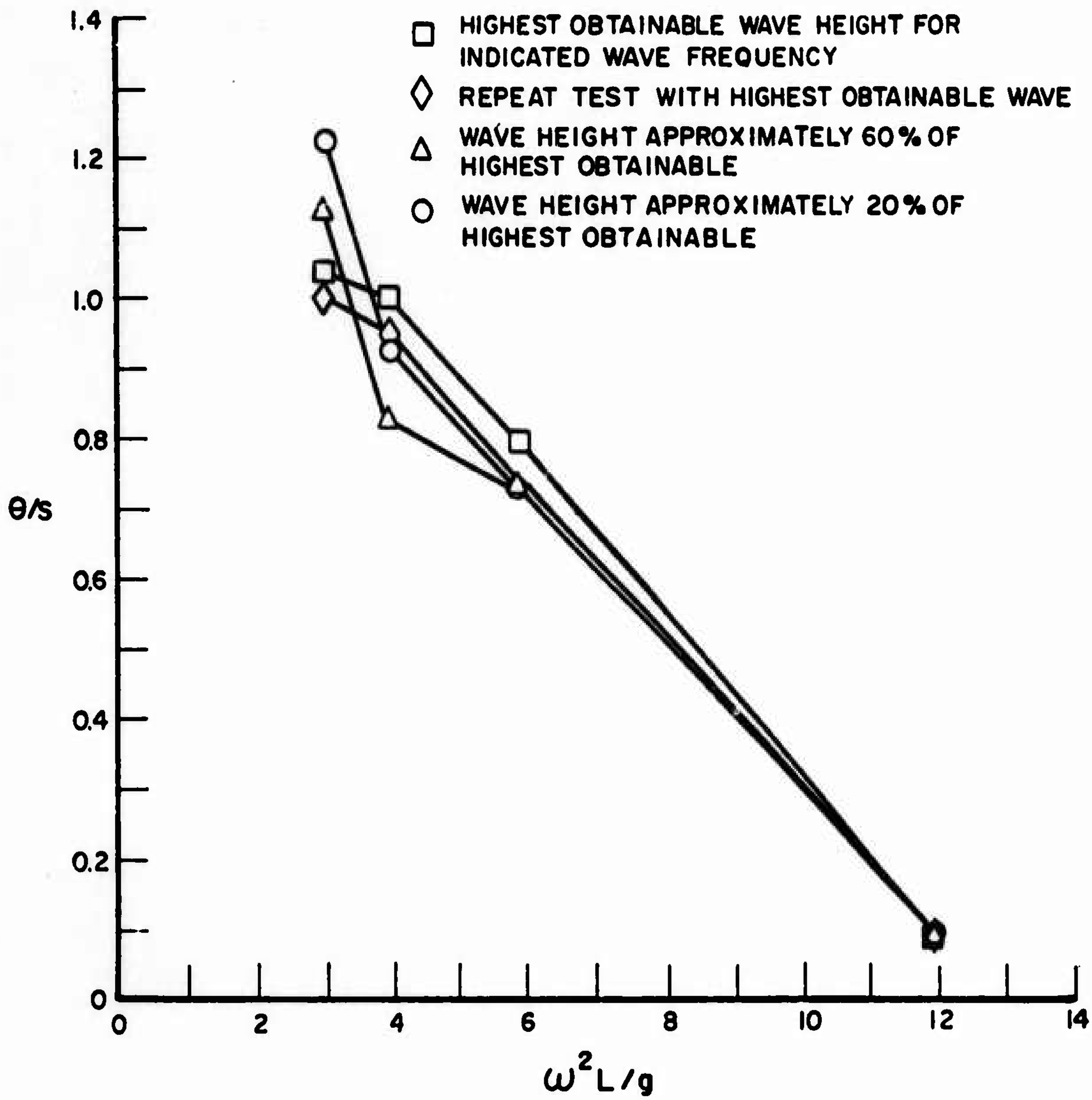

FIG. 4. PITCH RESPONSE OF CATHEDRAL HULL MODEL

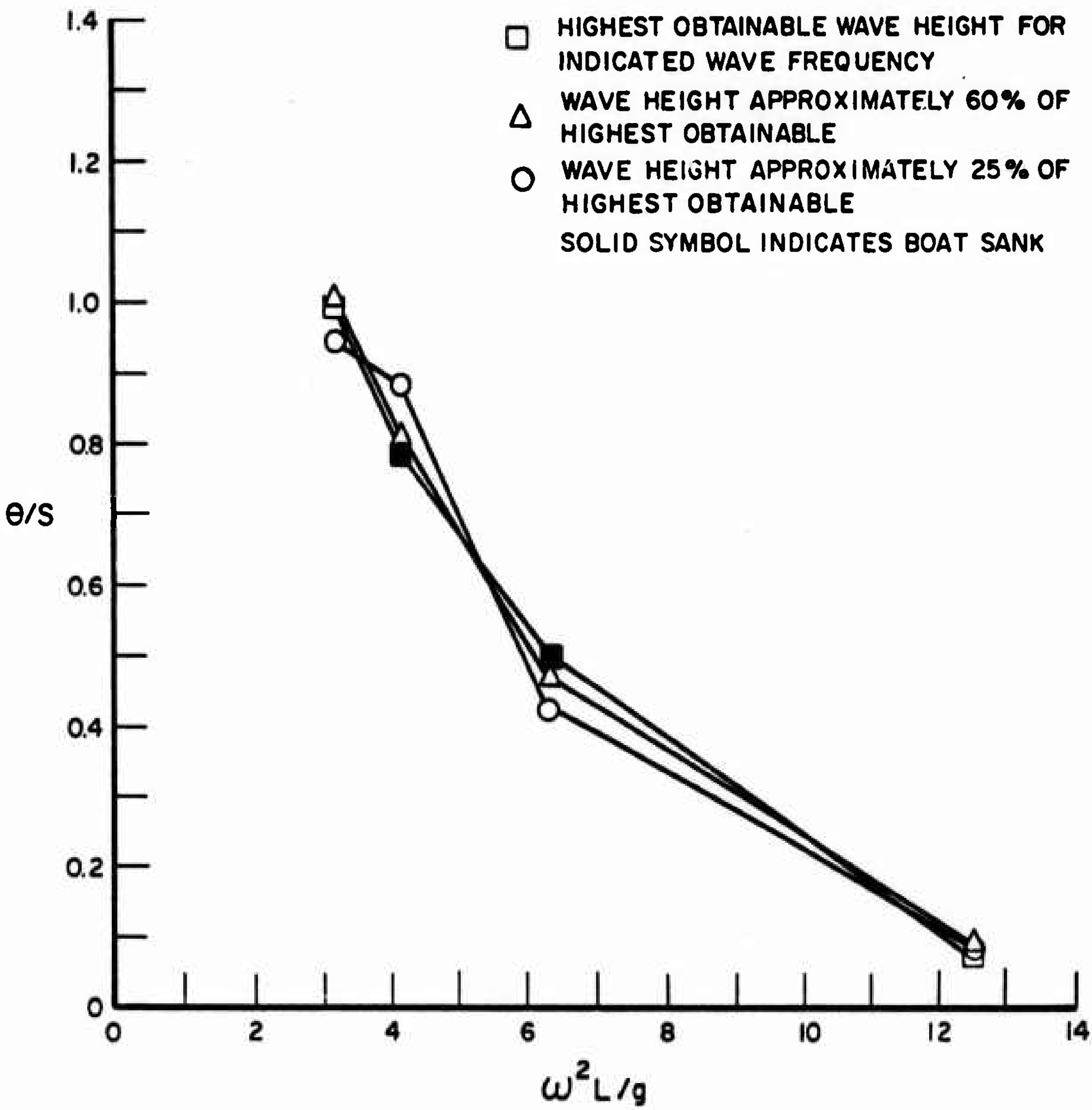

FIG. 5. PITCH RESPONSE OF THE JOHN BOAT MODEL

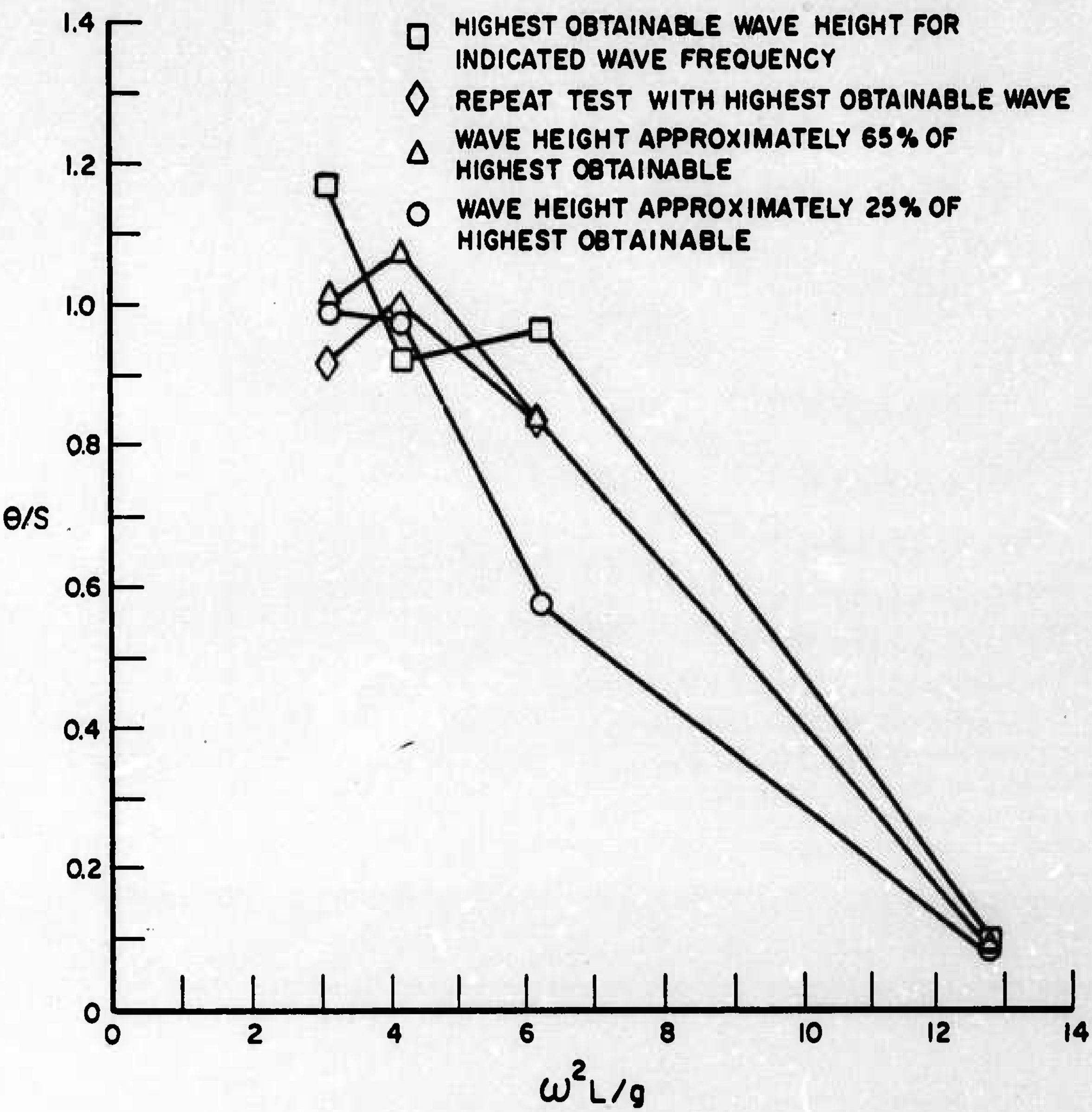

FIG. 6. PITCH RESPONSE OF THE DEEP VEE MODEL